Pacific Science (1997), vol. 51, no. 1: 54–75

Sea-Floor Geology of a Part of Māmala Bay, Hawai'i[1]

MONTY A. HAMPTON, MICHAEL E. TORRESAN, AND JOHN H. BARBER, JR.[2]

ABSTRACT: We surveyed the sea-floor geology within a 200-km^2 area of Māmala Bay, off Honolulu, Hawai'i, by collecting and analyzing sidescan sonar images, 3.5-kHz profiles, video and still visual images, and box-core samples. The study area extends from 20-m water depth on the insular shelf to 600-m water depth in a southeast-trending trough. The sidescan images depict three principal types of sea-floor material: low-backscatter natural sediment, high-backscatter drowned carbonate reef, and intermediate-backscatter dredged-material deposits. Cores indicate that the natural sediment is muddy sand, composed of carbonate reef and microfauna debris with some volcanic grains. Vague areal trends in composition are evident. The dredged material comprises poorly sorted, cobble- to clay-size mixtures of reef, volcanic, and man-made debris, up to 35 cm thick. Dredged-material deposits are not evident in the 3.5-kHz profiles. In the sidescan images they appear as isolated, circular to subcircular imprints, apparently formed by individual drops, around the periphery of their occurrence, but they overlap and coalesce to a nearly continuous, intermediate-backscatter blanket toward the center of three disposal sites investigated. We did not observe noticeable currents during our camera surveys, but there is abundant evidence of sediment reworking: symmetrical and asymmetrical ripples in the visual images, sand waves in the 3.5-kHz profiles and side-scan images, moats around the reefs in 3.5-kHz profiles, winnowed dredged material in the visual images, and burial of dredged material by natural sediment in cores. Most current indicators imply a westerly to northwesterly transport direction, along contours or upslope, although there are a few areas of easterly indicators. Internal waves probably drive the transport; their possible existence is implied by measured water-column density gradients.

MĀMALA BAY LIES OFF the south shore of the island of O'ahu, Hawai'i, between Diamond Head and Barbers Point (Figure 1). Notable nearby landmarks are Pearl Harbor and the city of Honolulu. We were contracted by the U.S. Army Corps of Engineers (USACE) and the U.S. Environmental Protection Agency (EPA) to map the sea floor and shallow subsea floor in part of the bay, as well as to collect and analyze sediment samples, in support of their programs to regulate and monitor the discharge of dredged material at offshore disposal sites. The study area covers about 200 km^2 between 21° 12′ and 21° 17′ N latitude and between 157° 49′ and 158° 03′ W longitude (Figure 1). Māmala Bay has been used as a repository for sediment dredged mainly from Pearl and Honolulu Harbors for more than a century, particularly at the three sites shown in Figure 1. The old Pearl Harbor and Honolulu Harbor sites have not been used since the South O'ahu site was designated in 1980. Since that time, a total of ca. 4.5 million m^3 of material has been dredged from Honolulu and Pearl Harbors and other areas.

In this paper we present the geologic results of our mapping and sampling program, focusing primarily on the bathymetry, sea-floor morphology, and sea-floor materials. Inferences are made about sediment transport. The geoenvironmental aspects of the dredged-material deposits are the subject of a paper to be presented elsewhere (see also Torresan et al. 1994).

[1] This study was supported by the U.S. Army Corps of Engineers and the Environmental Protection Agency. Manuscript accepted 5 April 1996.

[2] U.S. Geological Survey, Menlo Park, California.

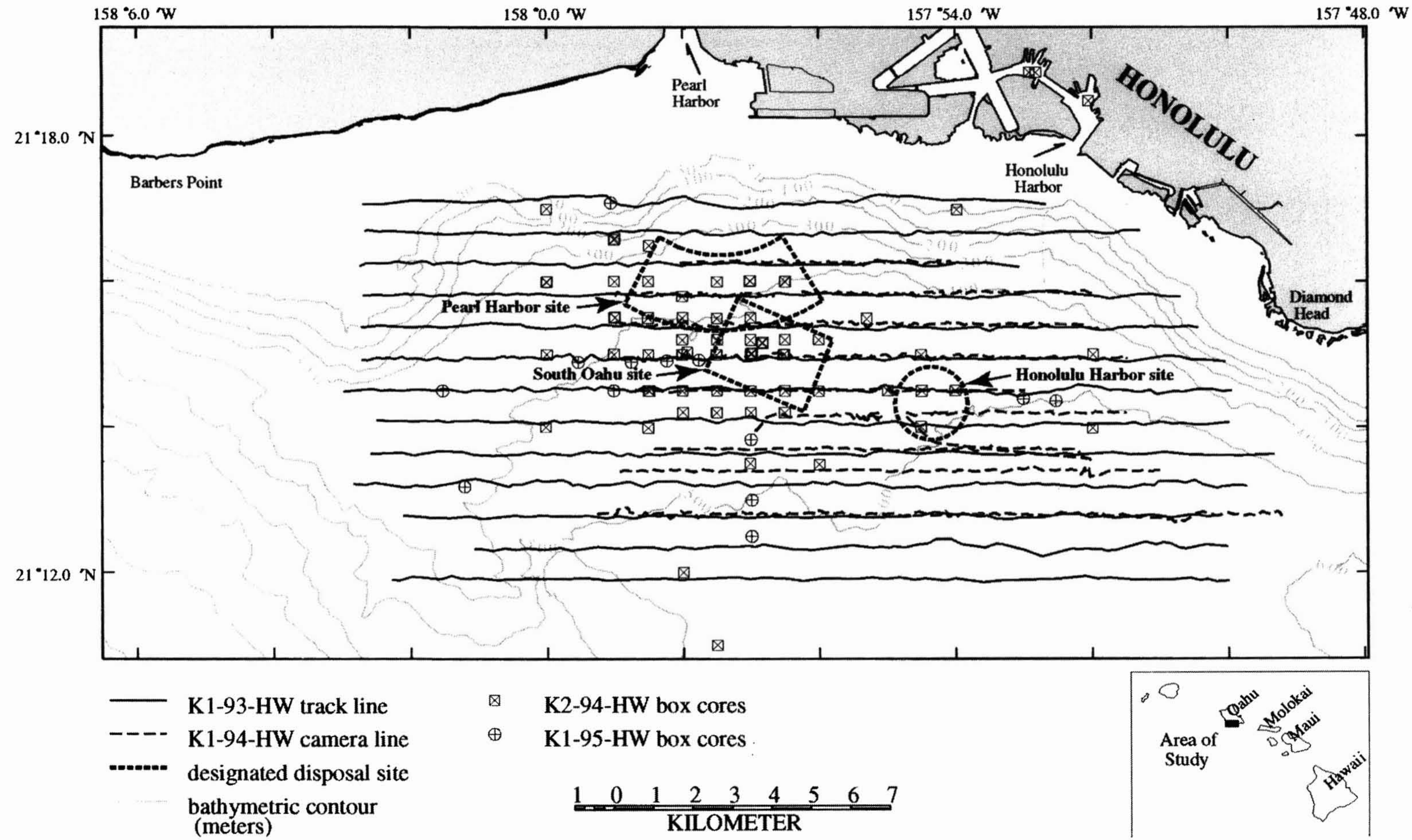


FIGURE 1. Location map, Māmala Bay, Hawai'i. Note that 3.5-kHz profiles and 12-kHz bathymetry measurements were collected along all tracklines.

MATERIALS AND METHODS

We conducted three cruises in Māmala Bay aboard the University of Hawai'i research vessel *Kila*. In February 1993, we used a sidescan sonar imaging system and a 3.5-kHz profiler to survey the sea floor. In May 1994 we used a box corer to collect sediment samples and a video/still-photo system to observe small-scale features of the sea floor, restricted to the vicinity of the dredged-material deposits, as shown in Figure 1. In June 1995 we collected more box-core samples. A camera was attached to the box corer in 1995 to obtain photographs of the sea floor at the sampling sites.

The transmitted pulse of the sidescan sonar was at 59 kHz, and 8968 samples per scan, digitized at 6 bits, were recorded on optical disk. The images were displayed real time on a graphic recorder with 16 levels of gray tone. We employed a 1-km swath width along tracklines, which were spaced at 800 m (Figure 1). The advertised spatial resolution of the system is 1/800 of the swath width, which equates to about 1.3 m for our survey. After collection, the sidescan data were processed to remove the water column and to make radiometric (shading, destriping and debanding, speckel removal, and nadir tonal improvement) and geometric (slant to ground range and aspect ratio) corrections (Chavez 1986), and a digital mosaic of the sidescan images was constructed by computer (Figure 2).

Acoustic-reflection records (3.5 kHz) and 12-kHz depth soundings also were collected along the survey tracklines. The 3.5-kHz data were collected at a 0.25-, 0.5-, or 1.0-sec pulse repetition rate. They were recorded on optical disk and displayed as profiles on a 16-bit format color monitor and on an ink-jet color printer. The 12-kHz system was run at 1-sec rate, and depths (assuming an acoustic velocity of seawater of 1500 m/sec) were stored with the digitized sidescan data and separately on optical disk.

The bottom camera system consisted of a 35-mm underwater still camera loaded with 15-m rolls of film (ca. 400 frames per roll) and a silicon intensified (SIT) black-and-white video camera with a real-time video link to the surface. Video images were recorded on 8-mm tape. Video was collected along the entire extent of the tracklines shown in Figure 1, and still photographs were taken about every 1.5 min as long as film was available. Unfortunately, there was no length scale in the camera system.

We used a box corer to collect 110 sediment samples (Figure 1). The cross section of the box was 20 by 30 cm, and the height was 45 cm. The longest sediment core was 33 cm.

Ship navigation employed a global positioning system (GPS) in either an autonomous or a differential mode, with nominal accuracies of about 100 m or 1–3 m, respectively. We did not navigate the sidescan towfish or the video-camera sled. Therefore, to achieve correct geographic registration of the mosaic we had to locate features on the 3.5-kHz profiles (collected at the known position of the ship) that also could be located on the mosaic and then shift the mosaic to its proper geographic position.

RESULTS

Bathymetry and Sea-Floor Morphology

The bathymetry and regional sea-floor topography are shown in Figures 1 and 3. The bathymetric depth points were obtained from our soundings and from the U.S. National Oceanographic and Atmospheric Administration's GEODAS archive. Water depths in the surveyed area vary from 20 to 600 m. The outer part of the Māmala Bay insular shelf appears along the northern edge of Figure 3. The shelf is less than about 50 m deep and extends a minimum distance of 600 m from shore off Diamond Head to a maximum of nearly 5000 m east of Barbers Point. An extensive prominent step exists at the seaward edge of the insular shelf, at water depths to about 100 m. It is the Māmala shelf (Ruhe et al. 1965), thought to have formed during the latest Pleistocene low stand of sea level, either by wave erosion or by reef construction (Stearns 1974, Gregory and Kroenke 1982). Our 3.5-kHz profiles indicate that the step typically is a planar notch cut into the otherwise steeper slope (Figure 4). Stearns (1978) observed a drowned reef on the Māmala shelf during submersible dives.

Seaward of the insular shelf is a broad trough that slopes gently at an average of about 1° in a south to southeast direction. Most of the study

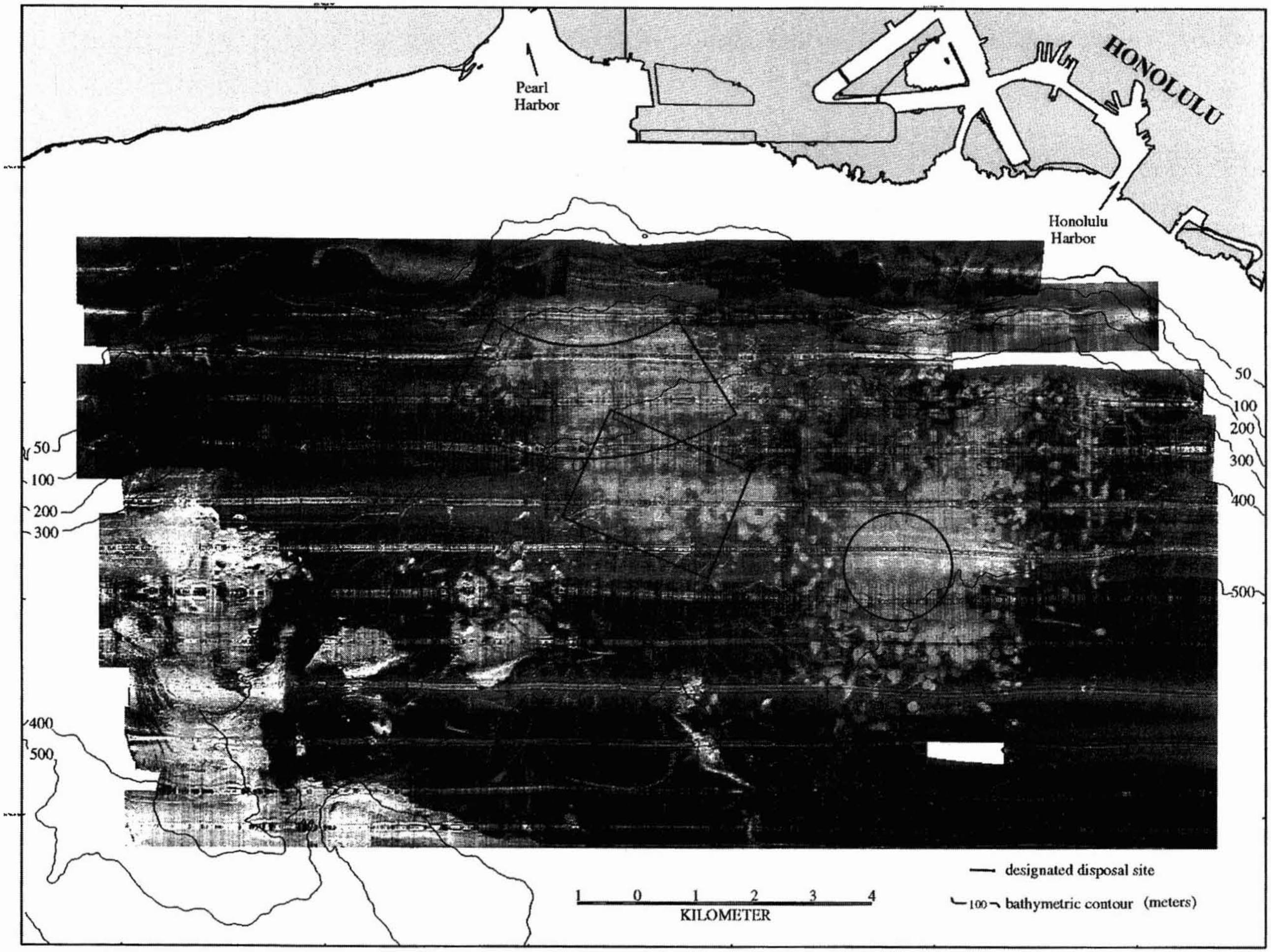


FIGURE 2. Sidescan sonar mosaic, with boundaries of designated dredged-material disposal sites indicated.

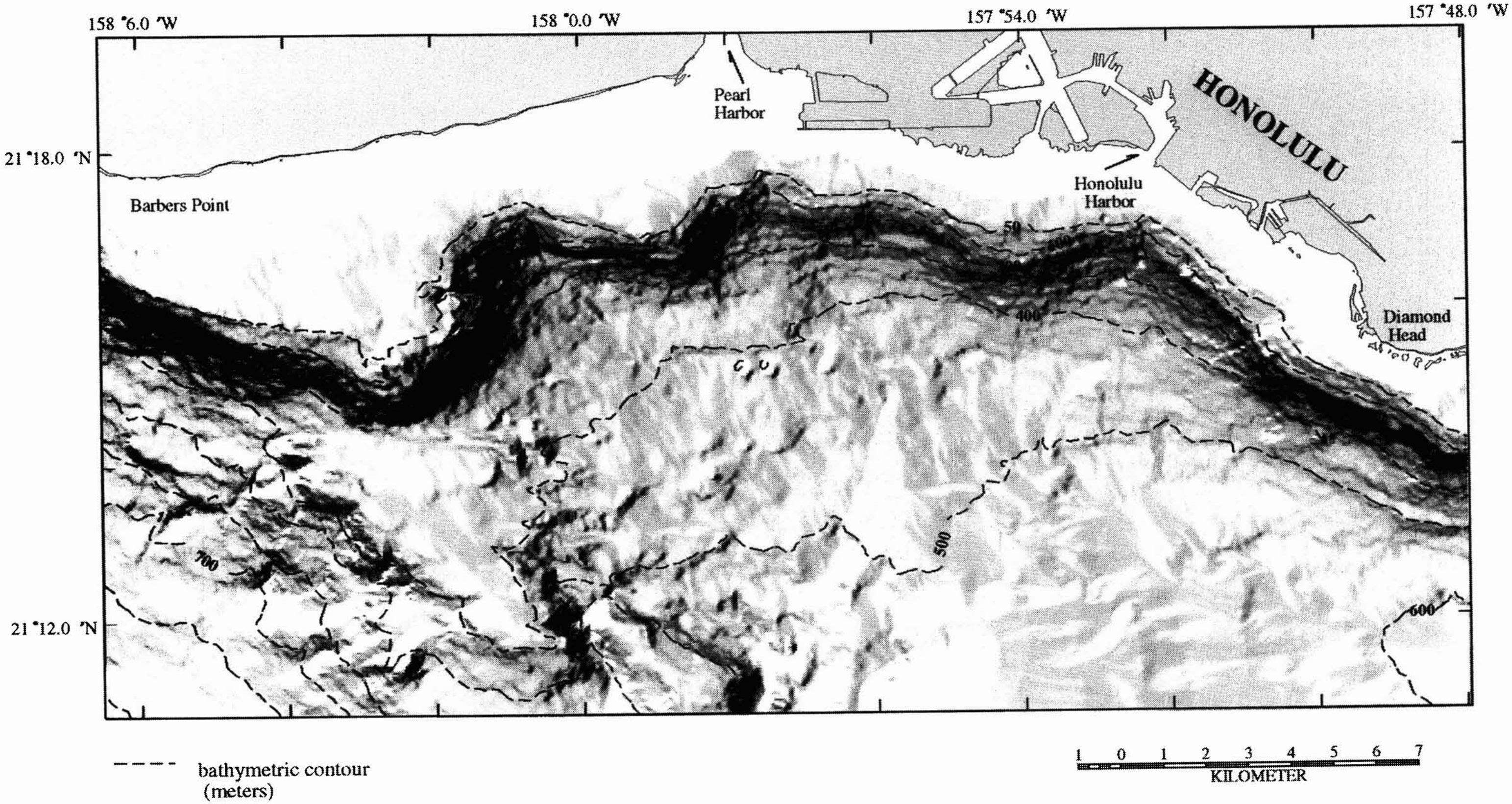


FIGURE 3. Shaded relief of the sea floor.

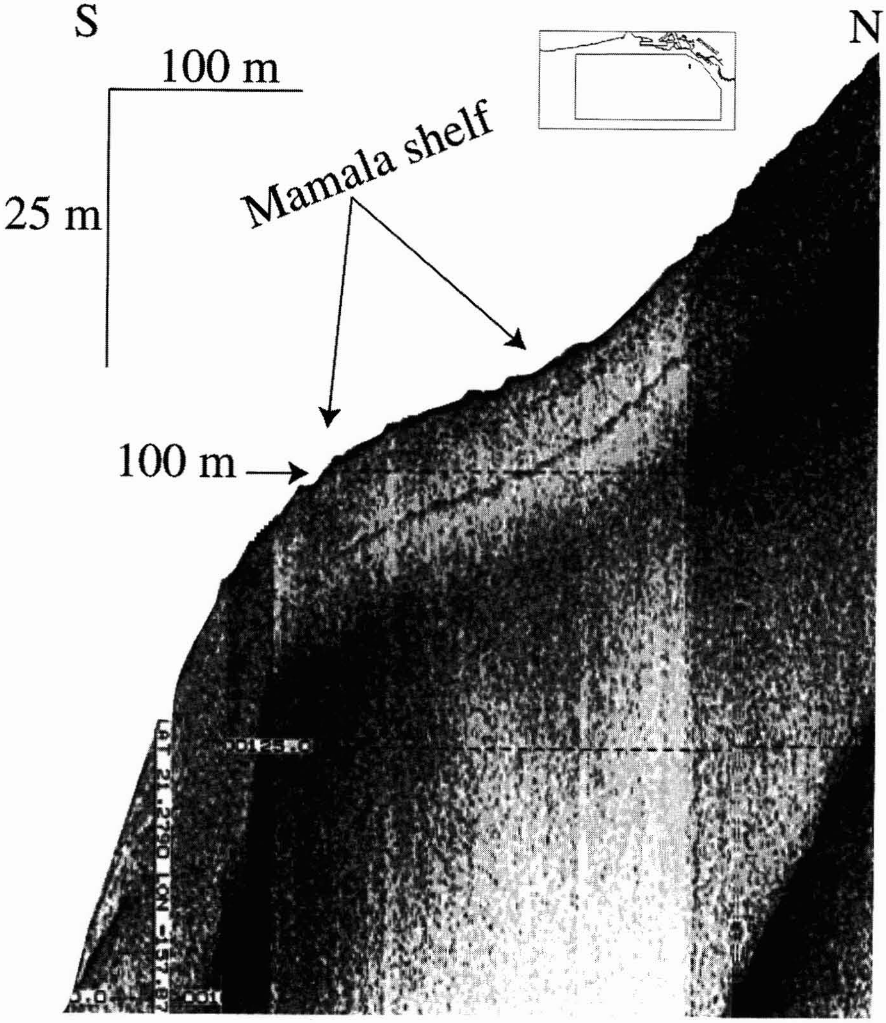


FIGURE 4. 3.5-kHz profile of the Māmala shelf that indicates a shoreline cut during a low stand of sea level.

area is contained within this trough. The head of the trough, from about 100 to 300 m water depth, is steep (~12°), cuspate shape, and has some local steps. The bathymetry map shows that the floor of the trough has slightly irregular topography generally of less than a few meters relief, although outcrops of drowned reefs approach heights of 50 m. The trough is bounded on the southwest by a southeast-trending platform that is underlain by a drowned reef (Gregory and Kroenke 1982) and dissected by a canyon. The platform extends seaward from the widest part of the insular shelf (Figure 3). The trough is bounded on the northeast by the steep slope that leads up to Diamond Head. The entire region greater than about 200–300 m deep is part of the Lualualei shelf (Stearns 1961), also known as the 500-m shelf (Kroenke and Woolard 1966). It is thought to have been sculpted into basaltic basement rocks by wave action, then locally overgrown by reefs during subsidence to its current depth (Gregory and Kroenke 1982).

Sea-Floor Materials

The sidescan mosaic displays three primary signatures that indicate different types of sea-floor material (Figure 2). The majority of the mosaic has a dark tone (low backscatter) that samples and visual images confirm is granular sediment. The light-toned (high backscatter), irregular, and sharply bounded shapes that extend primarily throughout the southwestern part of the mosaic are exposed carbonate reef and associated sediment. The areas of intermediate tone centered on, but extending well beyond, the disposal sites are the imprint of dredged-material deposits. Acoustic profiles presented by Gregory and Kroenke (1982) indicate a maximum sediment thickness of about 100 m over volcanic basement.

The low-backscatter sediment (here termed "natural" or "native" sediment), as confirmed by core samples, is predominantly tan-colored carbonate muddy sand and gravel. The grain size of several samples is shown in Figure 5*A*. The coarse fraction (>0.062 mm) is composed mostly of skeletal carbonate fragments of unidentifiable taxon, with lesser amounts of planktonic foraminiferal tests and basalt fragments. Up to a few percent echinoderm and bryozoan fragments, benthonic foraminiferal tests, volcanic mineral grains, and small mollusk shells also are present. Clay minerals are composed of poorly crystallized montmorillonite and halloysite/kaolinite. The amount of acid-insoluble residue, composed mostly of volcanic rock and mineral grains, varies from <1 to 35% (Figure 6*A*).

The composition of the natural sediment is areally variable, but only vague patterns of certain components are evident at our sampling density, as shown in Figure 7. There is a group of samples in the central part of the study area, with a northwest-southeast trend, that has a relatively high percentage of volcanic grains (10–50%). Several samples in the western part of the area have an orange color, evidently caused by iron staining, and the deepest-water samples tend to have large amounts of planktonic foraminifera (20–50%). Samples taken just seaward of a reef exposure at the edge of the insular shelf contain abundant gray to black carbonate fragments, giving the sediment a distinctive gray cast. A sample of the nearby reef contains large fragments of this material in addition to pieces of white coral.

The drowned reefs appear as isolated knobs or extensive rough sea floor in the profiles (Figure 8*A*) and as tan, craggy pinnacles or ledges in the camera images (Figure 8*B*). Local, small reef exposures occur outside the southwestern area. Many are visible on the sidescan mosaic and also on the profiles (for example, east of the old Pearl Harbor site). Several small reef knobs appear on the video images that are not apparent on the sidescan mosaic. A sample from one of the reefs consists of large coral fragments and carbonate sand. The distribution and history of the reefs were discussed by Gregory and Kroenke (1982), who concluded that they exist mainly on elevated areas of the volcanic basement and formed before and during the initial stages of subsidence.

The 3.5-kHz profiles show that the sea floor is high on the east side of most reef outcrops, and there is a topographic low, or moat, on the west side (Figure 8*A*). Extensive high-backscatter sediment covers the sea floor on the west side of the large reef outcrops along the southwestern side of the study area. A single sample reveals the sediment to be coarser grained than the low-backscatter natural sediment, and it is composed of carbonate sand with shell fragments a few millimeters in size and some larger pieces of coral.

The dredged-material deposits appear in the mosaic as isolated, circular to subcircular imprints, apparently formed by individual disposal drops, around the periphery of their occurrence. The imprints overlap and coalesce to a nearly continuous, moderate-backscatter blanket toward the center of the three disposal sites (Figure 2). In core samples, the dredged material typically is cohesive and olive green to black in color. It has a heterogenous composition and texture, with particles from clay to cobble size. It is typically muddier and contains larger gravel than the natural sediment. The grain size of several samples is shown in Figure 5*B*. The coarsest particles include pieces of reef carbonate, calcareous worm tubes, shells and shell fragments, volcanic clasts, mud balls, and man-made debris. The finer fragments include comminuted skeletal carbonate, basalt (some oxidized to a rust color), plant material, cemented clastic carbonate, echinoderm shells, pellets, coral, and rusted pieces of metal. The amount of acid-insoluble residue measured in 24 samples varies from 7 to 44% (Figure 6*B*). The greatest recovered thickness is about 35 cm (Figure 9). Nowhere is there convincing evidence of the dredged

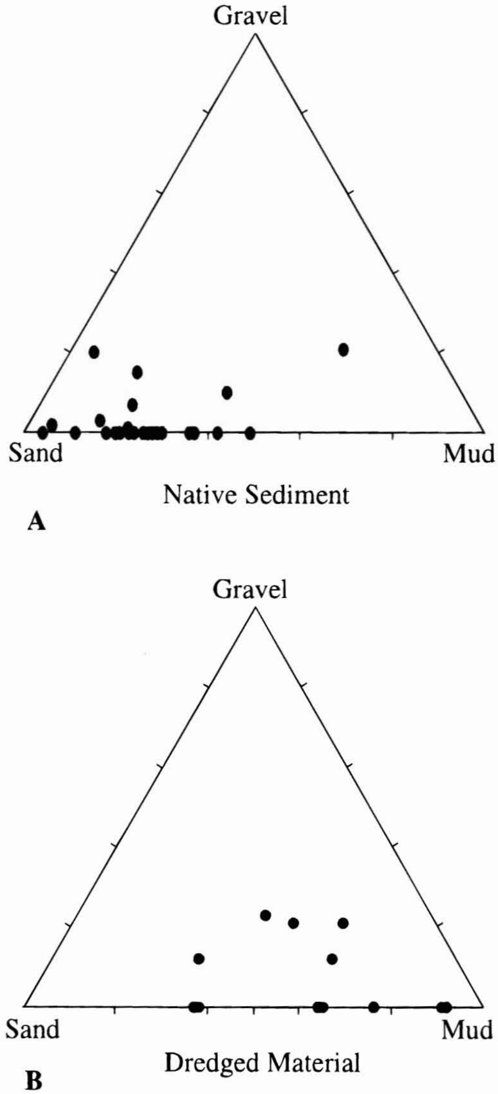


FIGURE 5. Grain size of samples of *A*, natural sediment and *B*, dredged material. Gravel size is greater than 2 mm, sand is between 2 mm and 0.062 mm, and mud is finer than 0.062 mm.

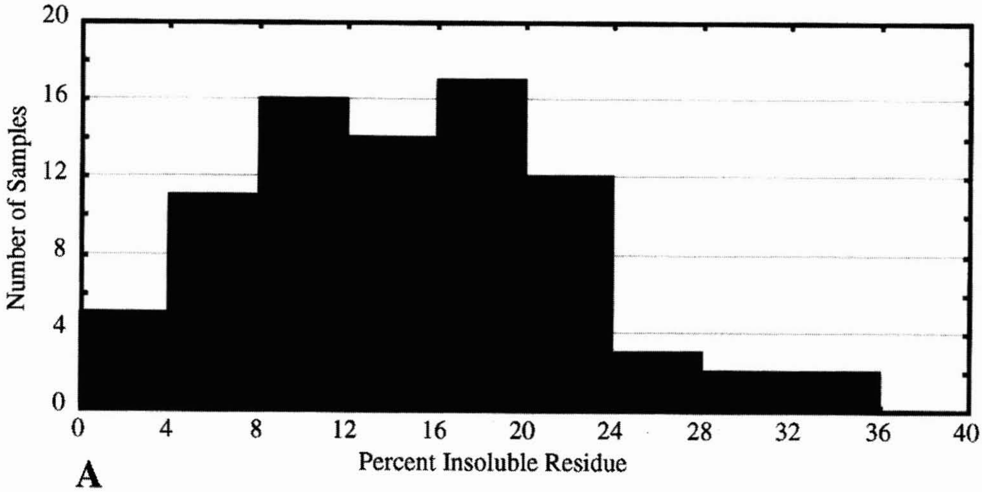
material in the 3.5-kHz profiles. The dredged material in the Honolulu Harbor site typically has larger maximum-size particles than in the other two sites.

A few cores have a thin layer of natural sediment that covers dredged material (Figure 10). In the camera images, the dredged material appears to either completely cover the sea floor in a single frame or be patchily interspersed with natural sediment, very sparsely in some places. There is a continuum between sparse and complete coverage (Figure 11*A,B*).

The camera images also show a multitude of man-made objects on the sea floor. Most numerous are vehicle tires, wire rope, metal structures, beverage cans, and ordnance.

Sedimentary Structures

Wavy bedforms are abundant throughout the study area. For example, ripples appear exten-



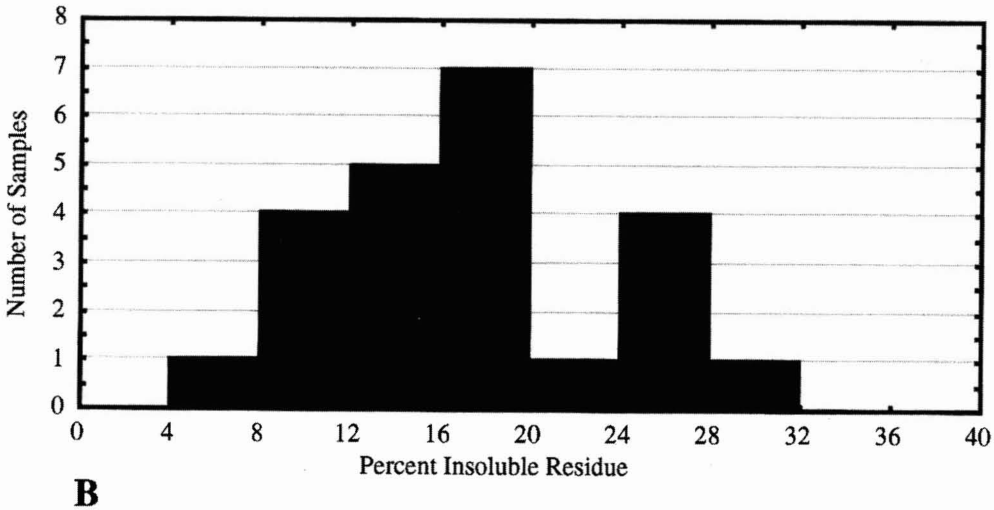


FIGURE 6. Histograms of the weight percent of insoluble residue in samples of *A*, natural sediment and *B*, dredged material.

sively in the camera images. There is a broad spectrum of ripple types, including symmetrical and asymmetrical forms (Figure 12). Crests commonly are sharp in profile, although they can be rounded, and in plan they are straight to curved and continuous to discontinuous. Some sections of the 3.5-kHz profiles show closely spaced hyperbolic diffractions (Figure 13) that can indicate the presence of rippled bedforms, which is confirmed where there are coincident camera images.

Bedforms larger than ripples are common also. A local area of asymmetric, sharp-crested megaripples is apparent along part of one video transect and on the accompanying 3.5-kHz profile (Figure 13). The 3.5-kHz profiles show relatively large waves, here termed sand waves, on the sea floor at many places where ripples appear in the photographs, and also beyond the camera transects (Figure 14). The waves tend to have rounded crests and nonuniform sizes. Most have symmetrical profiles, but some are asymmetrical, most facing in a westerly direction on east-west tracklines. The waves typically are less than

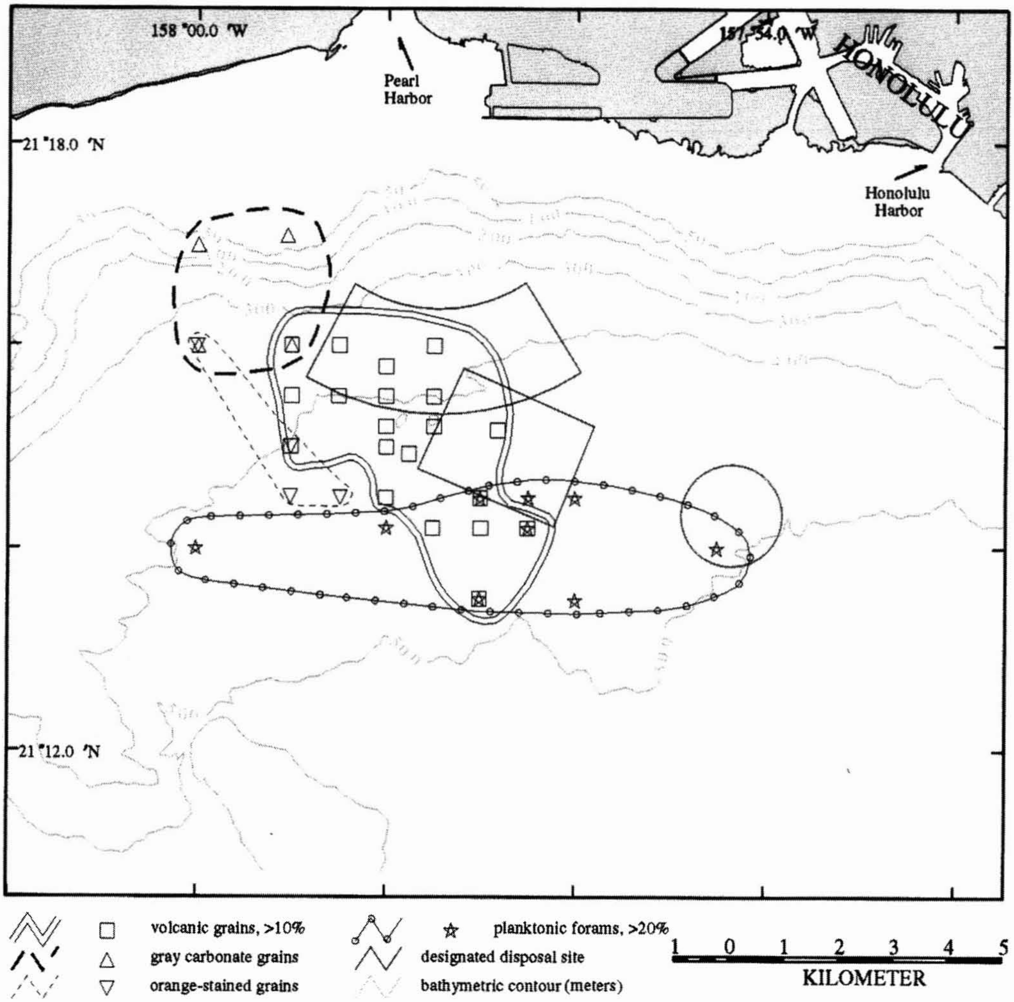
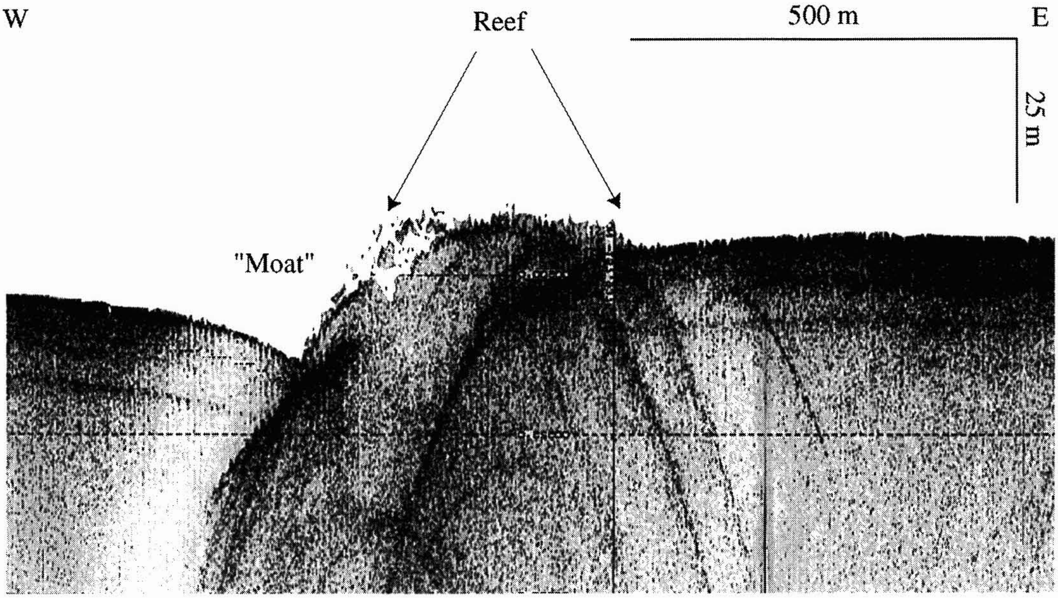


FIGURE 7. Map of areal distribution of sediment types. The indicated samples have abnormal composition compared to typical sediment collected at other stations.

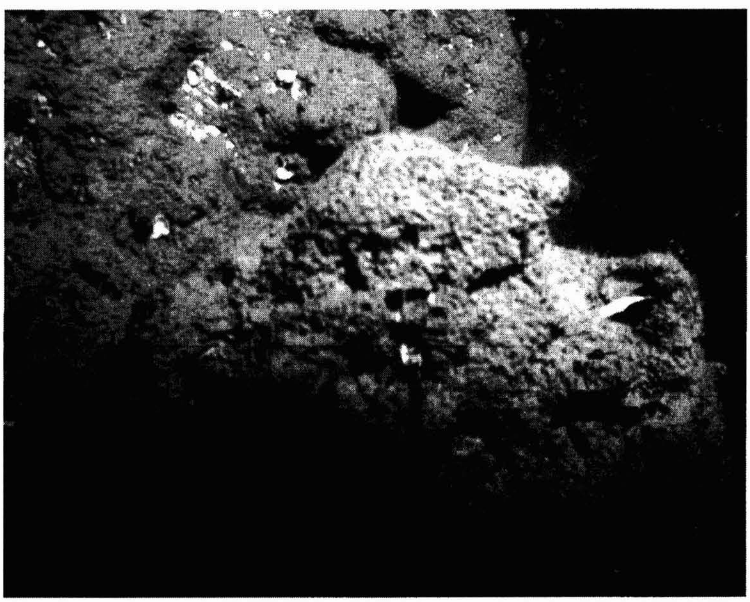
3 m high and up to 200 m wavelength. Many are underlain by a flat to wavy reflector, which distinguishes them from reef mounds. Linear features that represent the crests of wavy bedforms can be detected on the sidescan mosaic, both within the low-backscatter natural sediment and within the high-backscatter sediment adjacent to drowned reefs (Figure 15). Their trends are northwest to northeast.

Some ripples appear highly degraded, and others have crests that are short and disorganized. No inferences regarding current direction can be made for those ripples. However, many, if not most, ripples are fresh in appearance, and a dominant crestal trend can be discerned. Ripple type and orientation can change substantially over short distances. Although there is a large variance, most crests trend within 45° of north; that is, they are more north-south than east-west (Figure 16). The majority of asymmetrical ripples are short-crested, have a lunate or linguoid shape, and face upslope or along slope in a westerly to northwesterly direction; few face downslope. The megaripples mentioned above face east, as do their superimposed ripples.

Poorly developed ripples with disorganized



A



B

FIGURE 8. Reefs. *A*, 3.5-kHz profile of exposed reef; *B*, photograph of reef knob.

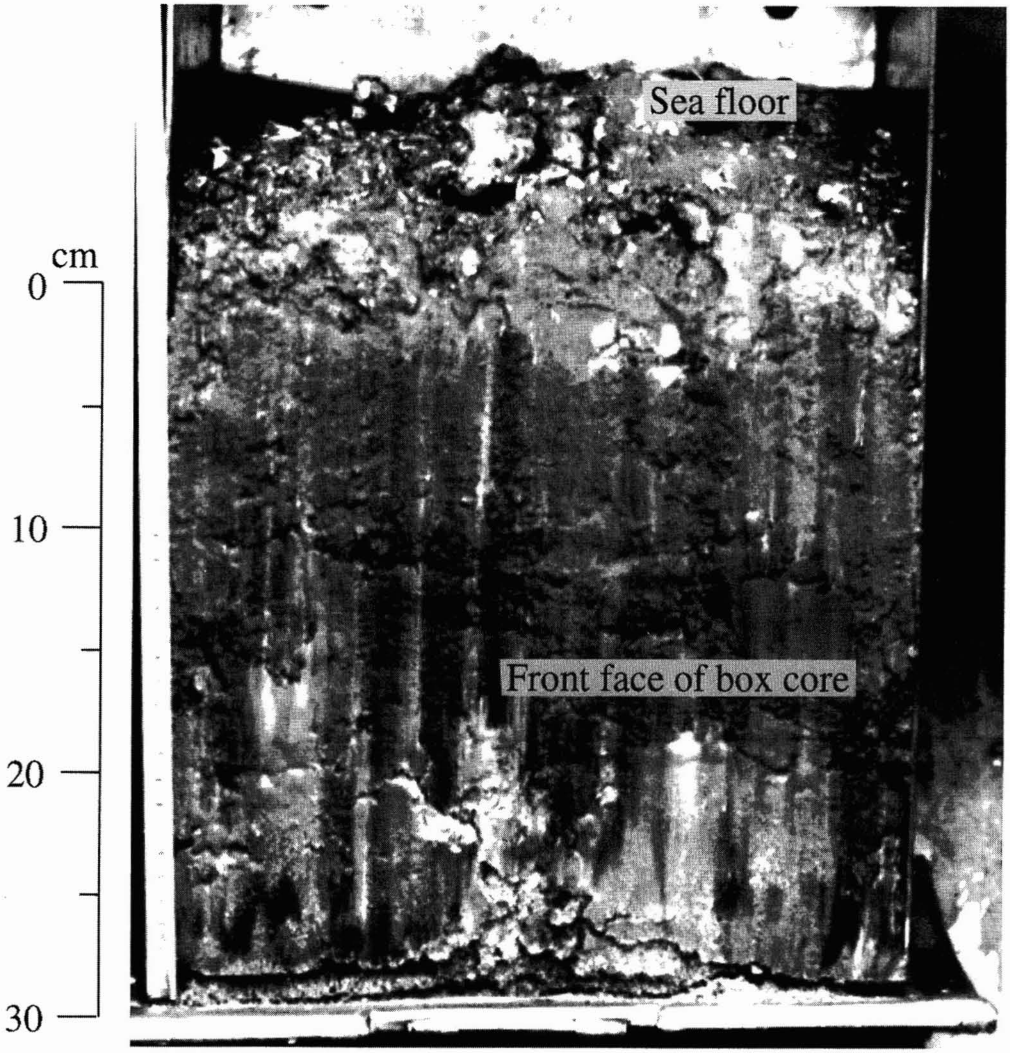


FIGURE 9. Photograph of box core that contains nearly 30 cm of dredged material.

crests occur where natural sediment is interspersed with dredged material (Figure 11*B*). However, ripples do not occur at all where dredged material continuously covers the sea floor, probably because the material is too cohesive and because there is too much coarse sediment. Disorganized ripples are common near, but outside, the dredged-material deposits also. Although some sort of bedforms are present most places along the camera transects, the sea floor appears exceptionally smooth in natural sediment near the eastern end of some.

Because the wavy bedforms described above are formed by currents and have implications about sediment dynamics, it is notable that during the camera surveys (10–15 May 1994) we did not detect any bedload sediment movement and only a few instances of suspended sediment transport, where weak currents apparently swept grains off nearby elevated reef outcrops. Also,

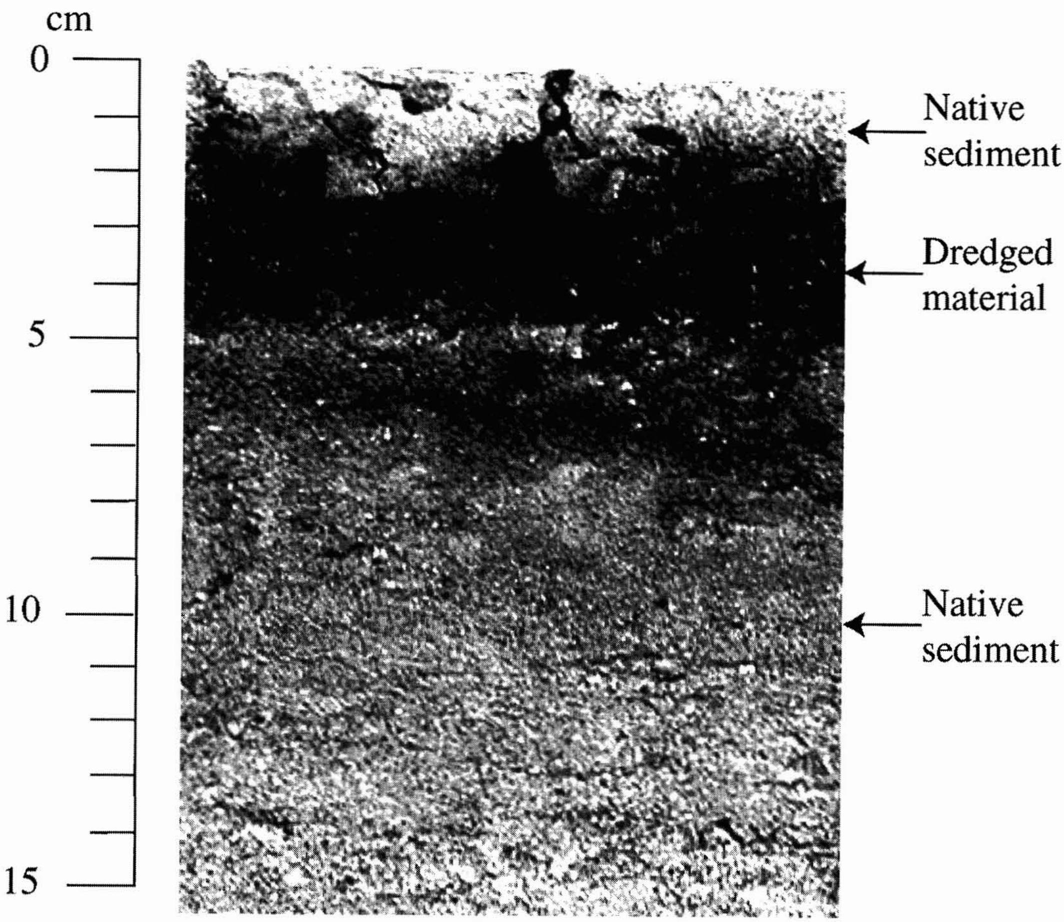


FIGURE 10. Photograph of a slab taken from the face of a box core, with a few centimeters of native sediment covering a few centimeters of dredged material that in turn overlies about 10 cm of native sediment.

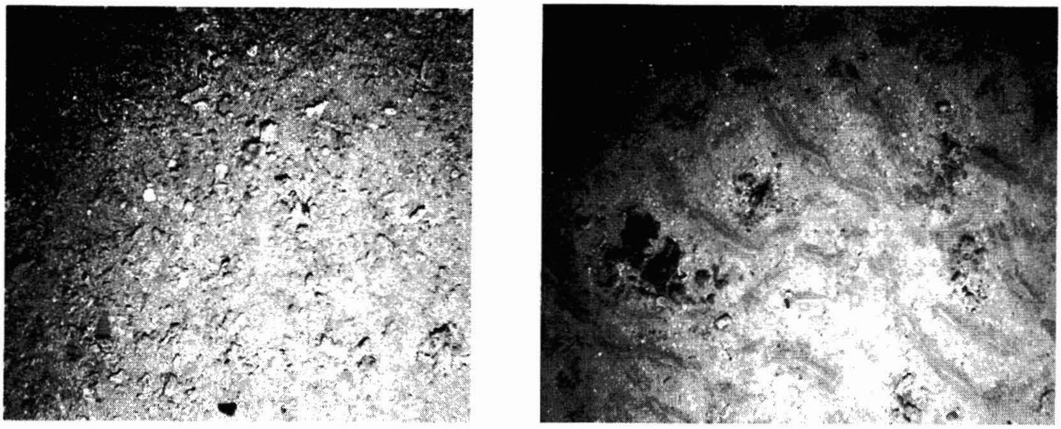
when the camera sled occasionally impacted the sea floor, the cloud of displaced sediment typically showed little or no deflection by currents as it collapsed. Currents were weak to nonexistent during our surveys, but the fresh appearance of many ripples suggests recent stronger currents in the area.

X-radiographs show that most samples are extensively bioturbated with some degree of subtle, original stratification. Unambiguous cross lamination is rare (Figure 17). Lebensspuren appear from place to place in the camera images, particularly in the northeastern part of the area. A few instances of small fish interacting with the sea floor and infauna emerging from burrows were seen, but overall, evidence of animal-sediment interaction at the sea floor was uncommon.

The sidescan images show enigmatic high-backscatter linear to curvilinear trains of short, parallel lines superimposed on the natural sediment in the southern and southwestern parts of the mapped area (Figures 2 and 18). They may or may not be bedforms. Individual lines are 50–100 m long and spaced at about 25–50 m, and individual trains of lines are up to 1 km long. No indications of these features appear in the other data types.

DISCUSSION

The sidescan mosaic and the box cores clearly distinguish three primary material types on the



A B

FIGURE 11. Photographs indicating *A,* complete and *B,* sparse coverage of the sea floor by dredged material.

sea floor of Māmala Bay, two natural (natural clastic sediment and carbonate reef) and one artificially emplaced (dredged material). The distinction between material types on the sidescan mosaic is made on the basis of backscatter strength, which evidently is primarily related to sea-floor hardness and/or roughness. Locally derived sediment is strewn around large reef outcrops, predominantly on the west side, and it is difficult to demarcate using backscatter strength alone. However, the 3.5-kHz profiles usually can be used to ascertain, on the basis of sea-floor morphology, the extent of actual reef outcrop, versus the high-backscatter sediment, along tracklines within the highest backscatter areas.

Although the dredged material can be distinguished easily from natural sediment in sidescan images, cores, and photographs, it cannot be reliably differentiated or mapped using the 3.5-kHz profiles. The reflectivity contrast, thickness, and relief of the dredged-material deposits are too small to appear distinctively on the profiles.

The camera images show extensive small ripples whose roughness apparently does not have a strong effect on the acoustic backscatter. Areas of smooth sediment, seen in camera images, do not differ visibly in sidescan backscatter strength from rippled sediment. The 3.5-kHz profiles record sand waves, and they appear in certain places on the sidescan images. Notably, they appear on some images but might be absent on the adjacent one, implying that survey conditions (e.g., sea state, transit direction) affected the basic image quality.

It is obvious that sea-floor sediment is at least occasionally remobilized by currents throughout most of the study area and that it has been reworked substantially since dredged material has been dumped in the area. The evidence comes from the extensive occurrence of wavy bedforms, the differences in sea-floor elevation on opposite sides of reef outcrops, and the local deposition of natural sediment on top of dredged material. The common symmetrical profiles of both the large and small wavy bedforms suggest that oscillatory currents are an important, probably dominant, reworking agent. Oscillatory currents also can produce asymmetrical bedforms if sufficient velocity asymmetry exists (Clifton 1976). The sediment reworking must be episodic because we detected no bedload transport during our surveys and very little evidence of currents. A similar situation of ripples formed by episodic currents was noted on the flank of Eniwetok Atoll by Shipek (1962).

Our data, both the long-term indicators such as the sea-floor morphology around reefs and the short-term indicators such as asymmetrical ripples, indicate predominantly west to northwest transport, either parallel to isobaths or upslope. Asymmetrical megaripples and their superimposed ripples indicate one particular

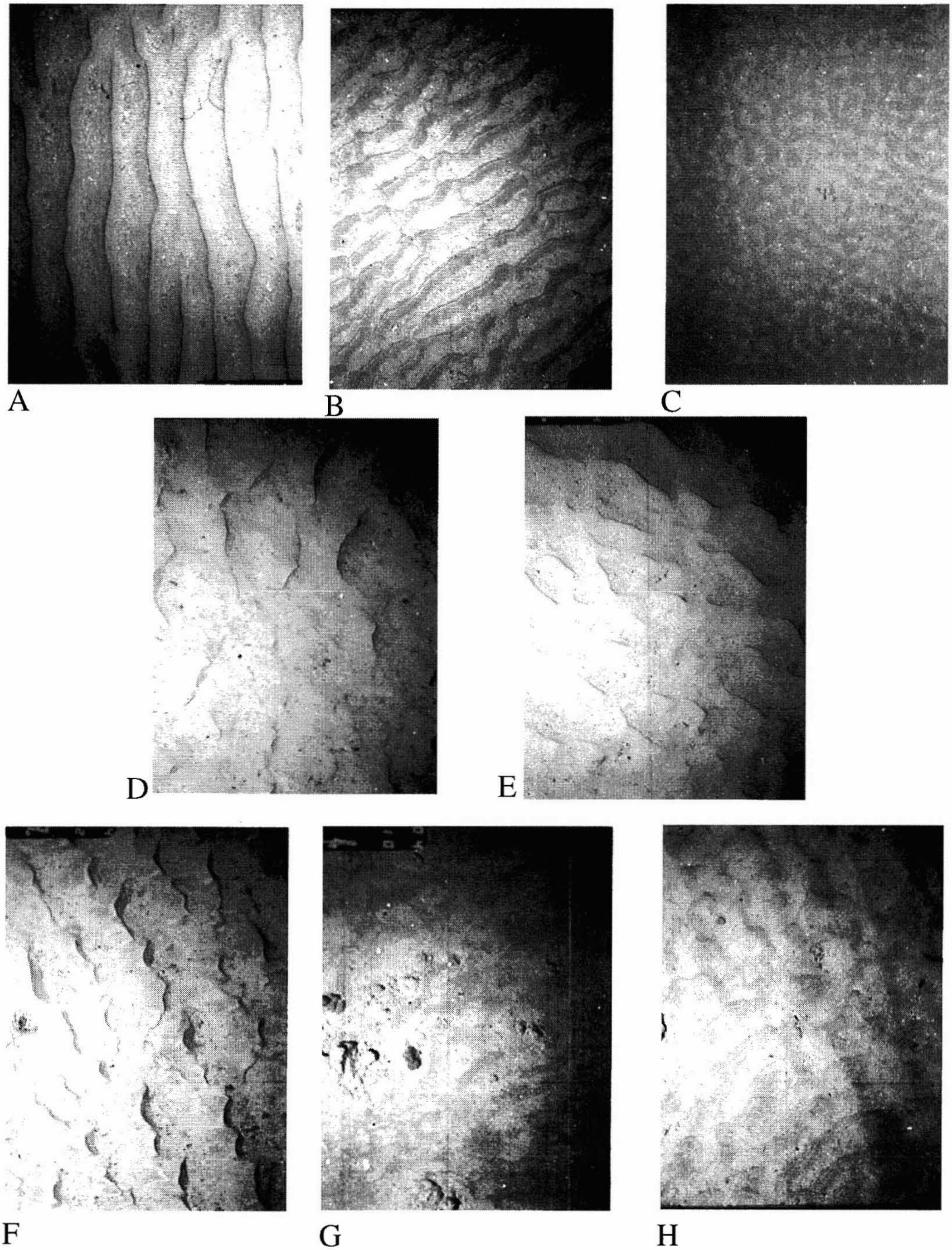


FIGURE 12. Photographs of a variety of ripple types in the study area. *A,* Symmetric ripples with long, sharp crests; *B,* long-crested asymmetric ripples with inferred net sediment transport direction to upper left (northwest); *C,* highly disorganized, short-crested ripples implying disrupted or multiple current directions; *D,* short-crested, lunate and linguoid asymmetric ripples with inferred current direction to lower right (southeast); *E,* short-crested, slightly asymmetric ripples facing toward upper right (northeast); *F,* short-crested, en-echelon asymmetric ripples with a dominant facing direction to the right (east); *G,* vaguely formed ripples around winnowed dredged material; *H,* symmetric ripples with bi-directional crest direction, from upper right to lower left and from upper left to lower right, implying two dominant current directions.

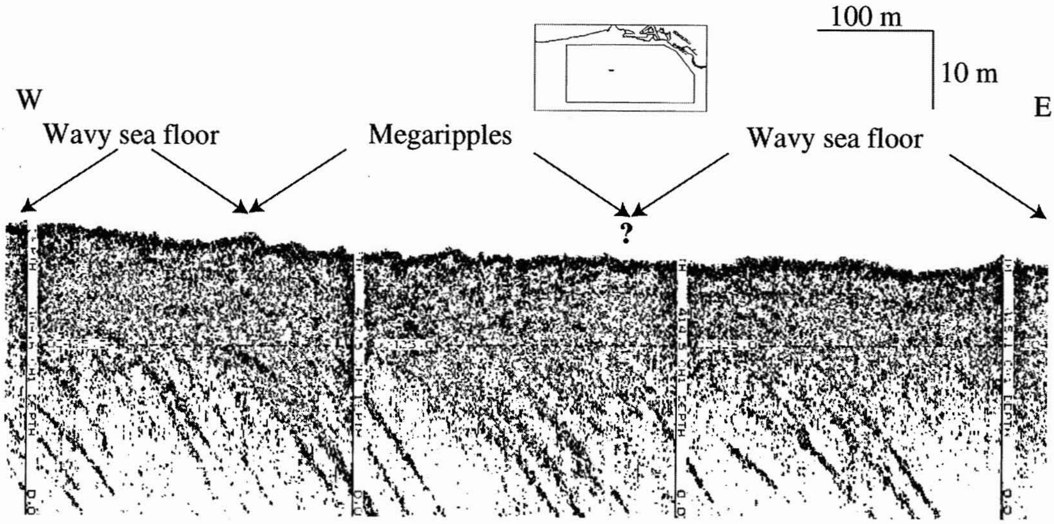


FIGURE 13. A 3.5-kHz seismic-reflection profile showing a short extent of megaripples within a field of larger sediment waves. Note the hyperbolic diffractions.

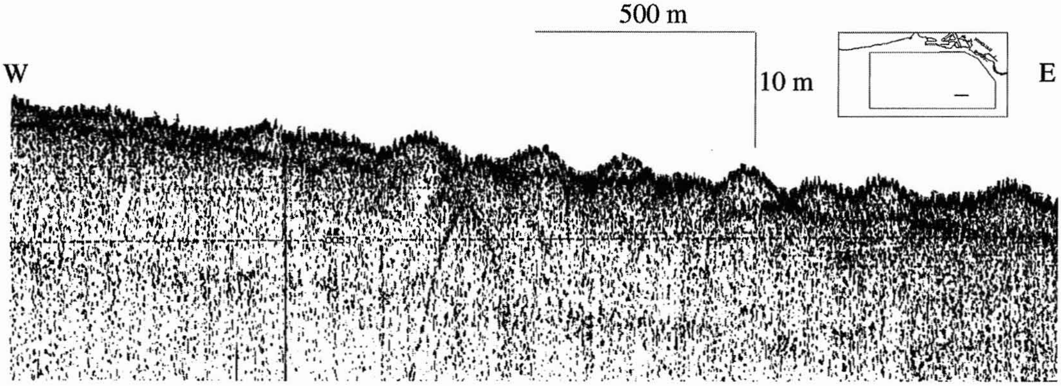


FIGURE 14. A 3.5-kHz profile of large-amplitude, symmetrical waves on sea floor. Note the reflector that underlies the waves.

area of eastward transport, and other more local instances were recorded.

The areal distribution of insoluble residue indicates sediment transport not only in a westerly direction, but also to the south. Two lines of samples, one extending west and the other extending south from the South O'ahu site, both show a generally decreasing amount of insoluble residue away from the site (Figure 19), which can be explained if dredged material (relatively high original insoluble residue content) is transported from its original depositional site and mixed into natural sediment (relatively low original insoluble residue content). In contrast, samples approaching the Honolulu Harbor site from the east consistently have moderately small contents of insoluble residue, probably close to the original amounts. The amount of insoluble residue in samples far from the disposal sites in any direction generally is small also. The smallest amounts, $<1\%$, occur in samples in shallow water at the steep head of the trough. These are the samples that also contain the gray carbonate fragments apparently derived from the nearby reef at the edge of the insular shelf.

A likely explanation of this distribution is

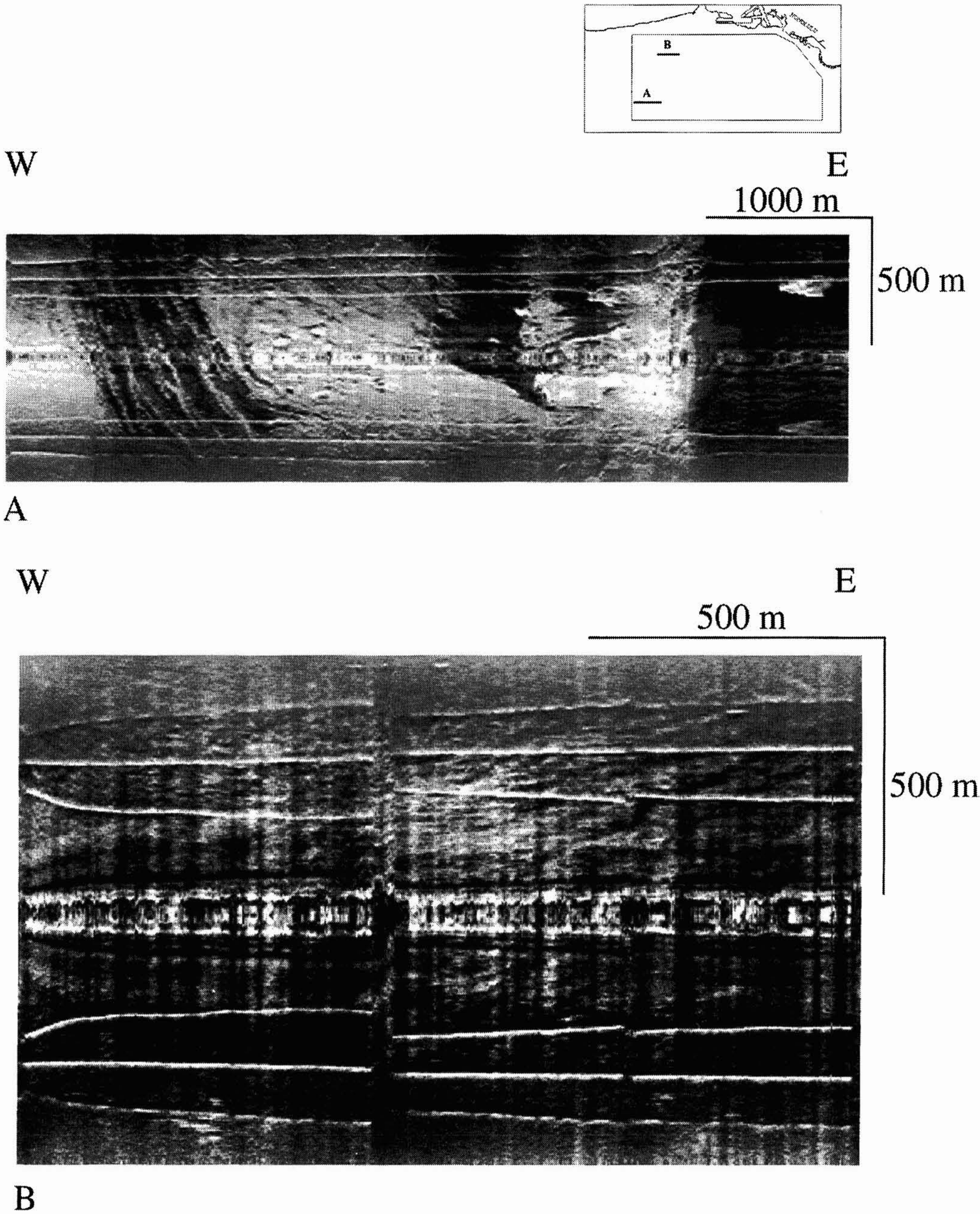


FIGURE 15. Sidescan images of sediment waves in *A*, high-backscatter sediment adjacent to exposed reef and *B*, within typical sandy native sediment.

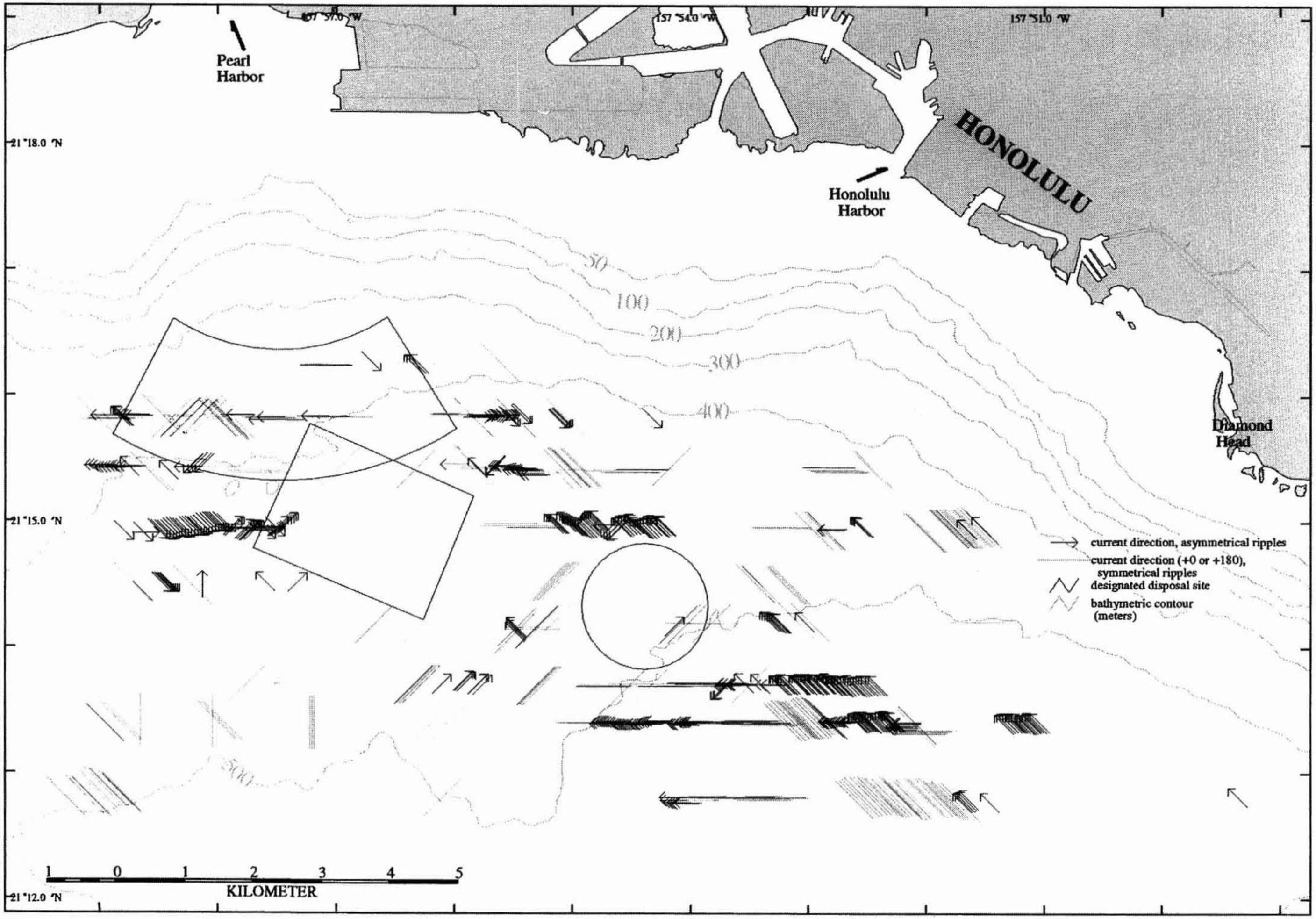


FIGURE 16. Map of current directions inferred from asymmetrical (lines with arrows) and symmetrical (no arrows) ripples.

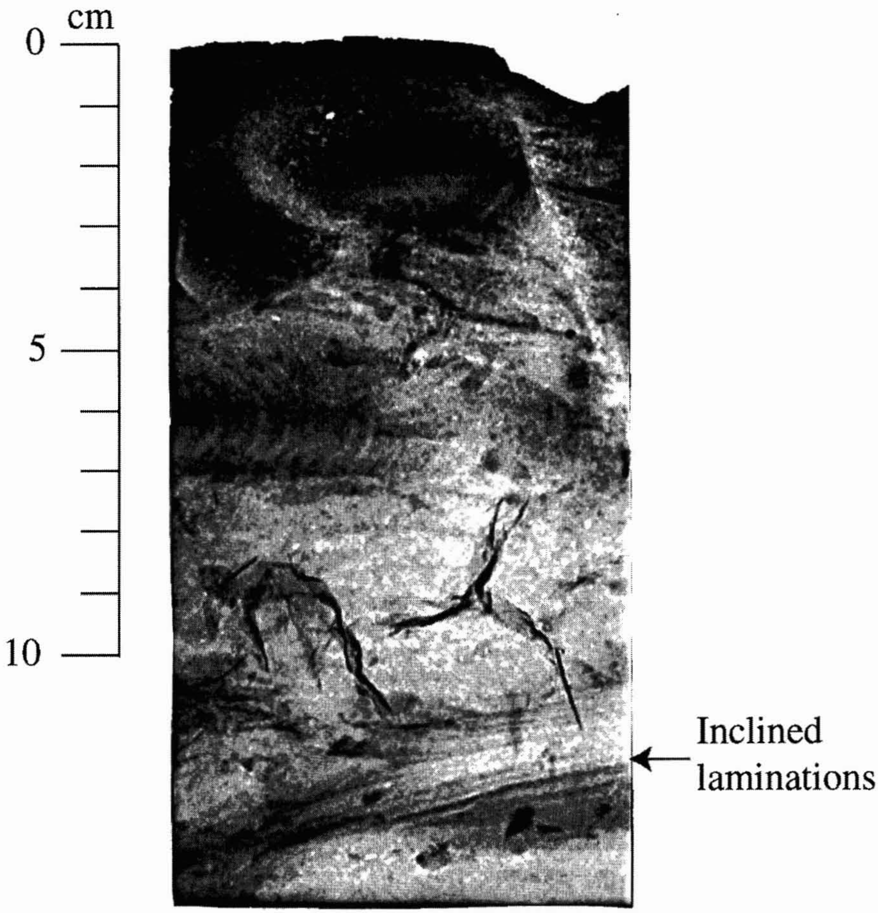


FIGURE 17. X-radiograph of slab taken from face of box core, showing abundant burrowing structures and a limited area of inclined laminations.

that, during lowered sea level, volcanic rock and mineral grains, which constitute most of the insoluble residue, were transported from the island across the emergent reef and mixed in small to moderate amounts with carbonate fragments, to be deposited in the deeper trough as natural sediment. Currently, dredged material supplies an enriched amount of insoluble residue, which is remobilized and mixed with natural sediment by westerly and southerly bottom currents, yielding the observed gradients away from the sites and the lack of a gradient approaching from the east. Sediment in samples from the steep head of the trough recently was transported over the edge of the insular shelf and has only small amounts of insoluble residue because most land-derived sediment is trapped in the estuaries and harbors during high stands of sea level.

Allen and Moberly (1977*a*) measured currents of up to 50 cm/sec velocity and net transport direction to the southwest within the Pearl Harbor disposal site, coincidently taken at the same time of year (May) as our 1994 survey. Shortly after a 7-week period of dredged-material disposal, they determined a southwesterly sediment dispersal pattern on the sea floor. The distribution became substantially more wide-

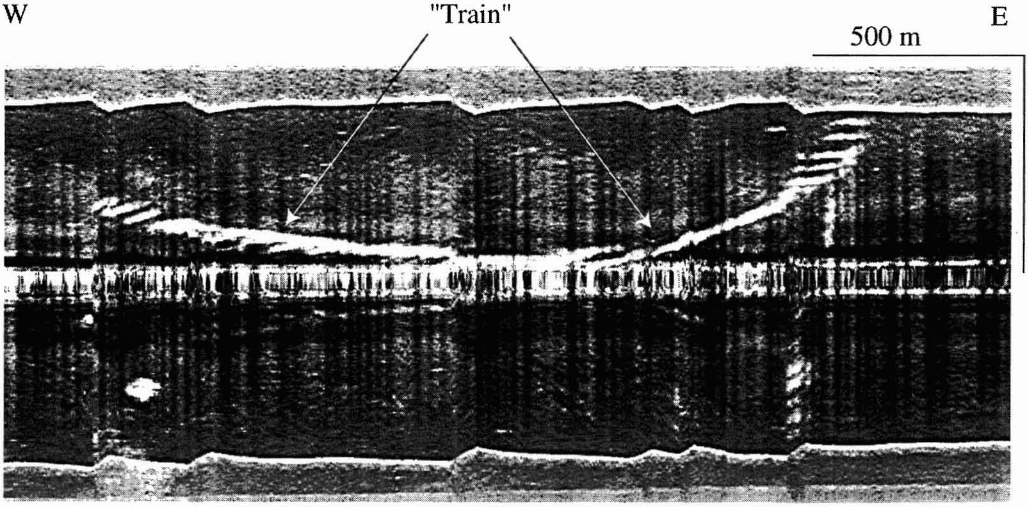


FIGURE 18. Sidescan image of enigmatic feature.

spread and omnidirectional 6 months after the disposal ceased (Allen and Moberly 1977*b*).

Allen and Moberly (1977*b*) determined that the measured currents were not principally the result of surface tides and mentioned internal waves as a possibility. We favor that suggestion, in light of strong vertical density gradients measured in the area (Neighbor Island Consultants 1977). Internal waves can mold large and small wavy bedforms of the types we observed (Southard and Cacchione 1972, Karl et al. 1986, Cacchione et al. 1988). Transport of sediment in an upslope direction by internal waves has been reported within bedform fields on Horizon Guyot (Lonsdale et al. 1972, Cacchione et al. 1988) and in large submarine canyons of the eastern Bering Sea (Karl et al. 1986). The return flow from breaking internal waves can transport sediment in the opposite direction of wave advance (Southard and Cacchione 1972), which perhaps accounts for the local area of easterly directed megaripples.

Our sidescan images, acoustic-reflection profiles, photographs, and sediment samples provide information about the sea-floor morphology, the distribution and composition of geological materials, and the sediment transport in Māmala Bay. We surmise that the natural sediment that covers most of the sea floor was deposited during Pleistocene low stands of sea level, derived mostly from the emergent reefs but with a small to moderate contribution eroded from the island's volcanoes. The sediment was deposited in a broad, southeast-trending trough, on and around drowned reefs, some of which remain exposed at the sea floor. Reef-derived sediment (e.g., the gray-colored sediment samples) apparently is now being deposited over the edge of the insular shelf, on the steep headwall of the trough. Most volcanic grains currently are trapped in coastal estuaries and harbors. We cannot discount the occasional occurrence of sediment gravity flows into deeper water, as has been documented off Kahe Point to the west (Tsutsui et al. 1987), but we saw no evidence of such activity.

Deposits of sediment dredged from Honolulu and Pearl Harbors, more than 30-cm maximum thickness, cover relict natural sediment and reefs over much of the study area and can be detected in all data sets except the 3.5-kHz profiles. Episodic bottom currents, most likely from internal waves, affect the sea floor, forming ripples and larger wavy bedforms over extensive areas and depressions (moats) on the down-current sides of the larger exposed reefs. The currents are oscillatory, but transport dredged material and natural sediment primarily in a net westerly to northwesterly direction, although there is evidence of southward transport also. Natural sediment is encroaching over and burying the dredged material in some places.

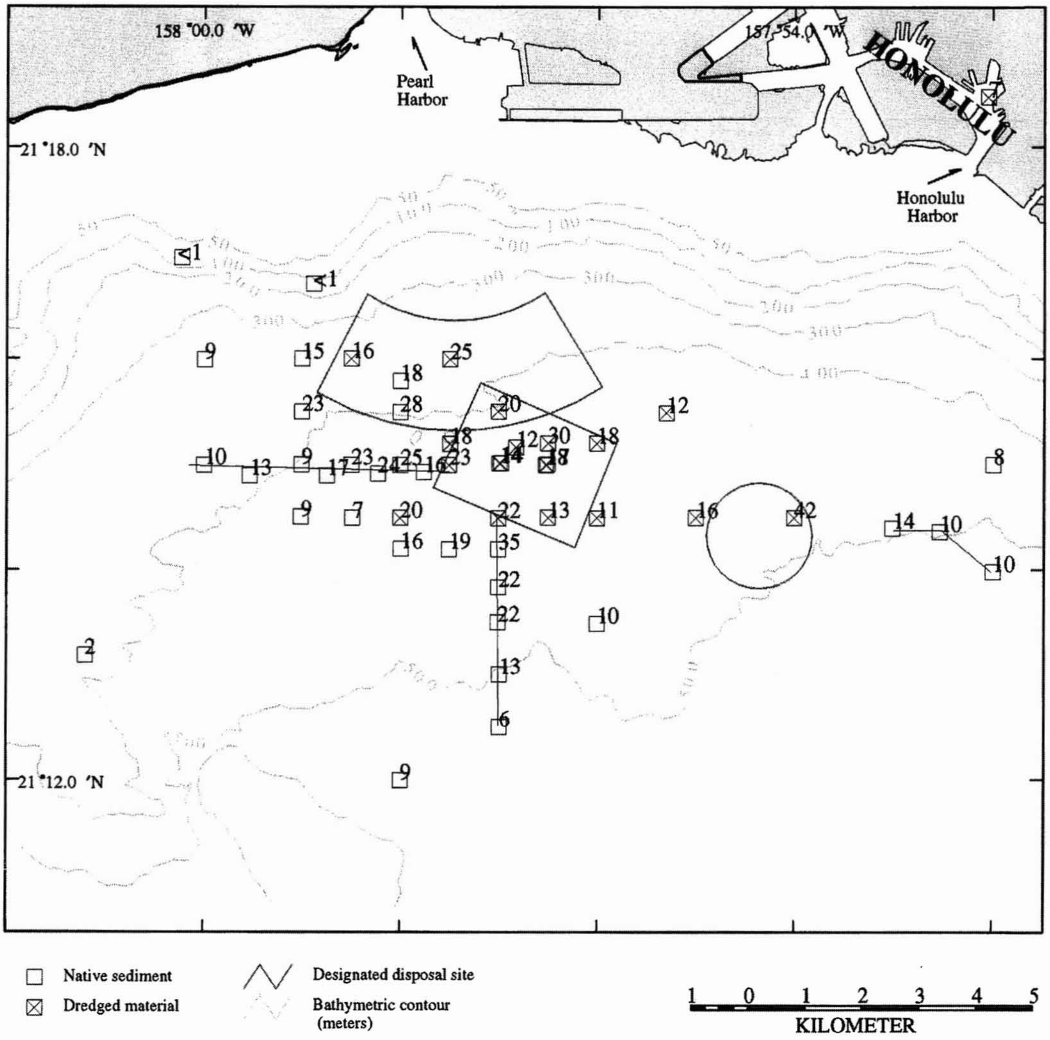


FIGURE 19. Weight percent of insoluble residue in native sediment and dredged material at the sea floor.

ACKNOWLEDGMENTS

We are grateful to the following U.S. Geological Survey colleagues for their technical assistance and discussions: David Cacchione, Thomas Chase, Marguerite Gowen, Gretchen Luepke, Larry Phillips, Paula Quinterno, Bruce Richmond, and Florence Wong. The crew of the R/V *Kila* provided excellent support to help us achieve our scientific goals. We are grateful to Michael Lee and Kathleen Dadey (USACE) and Allan Ota (EPA) for their encouragement and cooperation. Kathleen Dadey, Bruce Richmond, and David Twichell made helpful comments on the manuscript.

LITERATURE CITED

ALLEN, M. H., and R. MOBERLY. 1977*a*. Geology and physical oceanography. Part B. Pages III-1–III-43 *in* K. E. Chave and J. N. Miller, eds. Baseline studies and evaluation of the physical, chemical, and biological characteristics of nearshore dredge spoil disposal, Pearl Harbor, Hawaii. Final report to the Pacific Division Naval Facilities Engineering Command, University of Hawai'i Environmental Center, Honolulu.

———. 1977*b*. Geology and physical oceanography. Part C. Pages III-1–III-23 *in* K. E. Chave and J. N. Miller, eds. Baseline studies and evaluation of the physical, chemical, and biological characteristics of nearshore dredge spoil disposal, Pearl Harbor, Hawaii. Final report to the Pacific Division Naval Facilities Engineering Command, University of Hawai'i Environmental Center, Honolulu.

CACCHIONE, D. A., W. C. SCHWAB, M. NOBLE, and G. TATE. 1988. Internal tides and sediment movement on Horizon Guyot, Mid-Pacific Mountains. Geo-Mar. Lett. 8:11–17.

CHAVEZ, P. S., JR. 1986. Processing techniques for digital sonar images from GLORIA. Photogrammetric Eng. Remote Sens. 23:1133–1145.

CLIFTON, H. E. 1976. Wave-formed sedimentary structures—a conceptual model. Pages 126–148 *in* R. A. Davis and R. L. Ethington, eds. Beach and nearshore sedimentation. Soc. Econ. Paleontol. Mineral. Spec. Publ. 24.

GREGORY, A. E., and L. W. KROENKE. 1982. Reef development of a mid-oceanic island: Reflection profiling studies of the 500-meter shelf south of Oahu. Am. Assoc. Pet. Geol. Bull. 66:843–859.

KARL, H. A., D. A. CACCHIONE, and P. R. CARLSON. 1986. Internal-wave currents as a mechanism to account for large sand waves in Navarinsky Canyon head, Bering Sea. J. Sediment. Petrol. 56:706–714.

KROENKE, L. W., and G. P. WOOLARD. 1966. Seismic reflection investigations in the vicinity of the Hawaiian Ridge. Report HIG-65-11, Hawai'i Institute of Geophysics, Honolulu.

LONSDALE, P., W. R. NORMARK, and W. A. NEWMAN. 1972. Sedimentation and erosion on Horizon Guyot. Geol. Soc. Am. Bull. 83:289–316.

Neighbor Island Consultants. 1977. Final report. Environmental surveys of deep ocean dredged spoil disposal sites in Hawaii. Vol. I and II. Prepared for U.S. Army Corps of Engineers, Honolulu, Hawai'i.

RUHE, R. V., J. M. WILLIAMS, and E. L HILL. 1965. Shorelines and submarine shelves, Oahu, Hawaii. J. Geol. 73:485–497.

SHIPEK, C. J. 1962. Photographic survey of sea floor on southwest slope of Eniwetok Atoll. Geol. Soc. Am. Bull. 73:805–812.

SOUTHARD, J. B., and D. A. CACCHIONE. 1972. Experiments on bottom sediment movement by breaking internal waves. Pages 83–97 *in* D. J. P. Swift, D. B. Duane, and O. H. Pilkey, eds. Shelf sediment transport. Dowden, Hutchinson and Ross, Stroudsburg, Pennsylvania.

STEARNS, H. T. 1961. Eustatic shorelines on Pacific Islands. Z. Geomorphol. 3:3–16.

———. 1974. Submerged shorelines and shelves in the Hawaiian Islands and a revision of some of the eustatic emerged shorelines. Geol. Soc. Am. Bull. 85:795–804.

———. 1978. Quaternary shorelines in the Hawaiian Islands. Bishop Museum Press, Honolulu.

TORRESAN, M. E., J. H. BARBER, M. A. HAMPTON, P. DARTNELL, H. CHEZAR, M. W. MCLAUGHLIN, M. H. GOWEN, and L. L. ZINK. 1994. Ground truthing high-backscatter dredged material deposits in Mamala Bay, Honolulu, Hawaii. EOS Trans. 75(44): 319.

TSUTSUI, B., J. F. CAMPBELL, and W. T. COULBOURN. 1987. Storm-generated episodic movements off Kahe Point, Oahu, Hawaii. Mar. Geol. 76:281–289.